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Hierarchical Goal Analysis of dynamic decision making in microworld experiments

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Defence R&D Canada
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In conducting the research described in this report, the investigators adhered to the policies and procedures set out in the Tri-Council Policy Statement: Ethical conduct for research involving humans, National Council on Ethics in Human Research, Ottawa, 1998 as issued jointly by the Canadian Institutes of Health Research, the Natural Sciences and Engineering Research Council of Canada and the Social Sciences and Humanities Research Council of Canada.

Abstract

Recent developments in microworld-based experiments provide researchers with an opportunity to conduct complex and dynamic experiments in laboratory-controlled environments, thus narrowing the gap between laboratory-based and field experiments. The performance assessment in a dynamic decision making environment, however, requires new methods for evaluation and analysis of data and cognitive systems. This memorandum discusses the application of Hierarchical Goal Analysis (HGA) to evaluate cognitive systems in a distributed team environment.

The process of conducting HGA involves the following steps: a) derivation of goal hierarchy, b) assignment of goals to subjects, c) identification of controlled variables, and d) completion of templates that specify goal attributes. The HGA-derived controlled variables provide additional measurements of performance that are closely related to subjects' decisions. We conducted upward information flow and stability analyses to evaluate the system that the subjects were functioning in. The analyses helped to identify a number of situations that might impede subjects' performance during task execution.

Finally, this memorandum discusses the potential benefits of applying HGA in the context of distributed and dynamic simulations and proposes future work to use the HGA outputs as the basis for the development of a computational model for predicting subject performance under specific task conditions.

Résumé

Les récents développements dans le domaine des expériences basées sur les micromondes permettent aux chercheurs de mener des expériences complexes et dynamiques dans des environnements contrôlés en laboratoire, ce qui permet de réduire l'écart entre ce type d'expériences et celles menées sur le terrain. Toutefois, l'évaluation du rendement dans un environnement dynamique de prise de décisions exige de nouvelles méthodes d'évaluation et d'analyse des données et des systèmes cognitifs. Le présent document se penche sur l'utilisation de l'analyse des buts hiérarchiques (ABH) pour évaluer les systèmes cognitifs dans un environnement où les membres d'une équipe sont dispersés à plusieurs endroits.

Le processus lié à la réalisation d'ABH fait appel aux étapes suivantes : a) dérivation de la hiérarchie des buts, b) attribution de buts aux sujets, c) identification des variables contrôlées, d) réalisations de modèles qui précisent les attributs des buts. Les variables contrôlées dérivées de l'ABH fournissent des mesures additionnelles du rendement qui sont liées étroitement aux décisions des sujets. Nous avons réalisé des analyses des cheminements ascendants de l'information et de la stabilité de ce cheminements afin d'évaluer le système dans lequel les sujets se trouvent. Les analyses ont aidé à identifier un certain nombre de situations qui pourraient nuire au rendement des sujets lors de l'exécution de la tâche.

Pour terminer, ce document examine des avantages potentiels liés à l'application de l'ABH dans le contexte des simulations dynamiques impliquant des équipes réparties et nous proposons d'autres travaux qui pourraient utiliser à l'avenir les résultats de l'ABH comme base pour la mise au point d'un modèle computationnel permettant de prévoir le rendement du sujet sous certaines conditions de réalisation de tâche.

Executive summary

Hierarchical Goal Analysis of dynamic decision making in microworld experiments:

Zotov, Vlad; Chow, Renee; DRDC Toronto TM 2008-211; Defence R&D Canada – Toronto; February 2009

Background: The Canadian Forces (CF) are engaged in domestic and international operations that require co-ordination with allies, non-government organizations, and other groups that are often widely distributed. A scientific approach to analysis of distributed team performance is important for developing new tools or processes to improve the effectiveness of distributed teams. Such an approach needs to include means of identifying required levels of team performance, observing actual performance, and comparing actual performance to required performance to assess where and how improvements may be made. In order to outline the required performance we need to know what constitutes an optimal decision under the conditions that subjects perform their task. Hence, we needed a) an experimental platform that allowed capturing important characteristics of the real team dynamics, and b) a method to analyze distributed team performance in such a task.

To meet our objectives, we analyzed distributed team performance in C^3Fire [1] (C^3 stands for command, control, and communication) experimental platform by applying Hierarchical Goal Analysis (HGA) [2]. Microworlds are simplified, computer-generated replicas of the real world. The C^3Fire microworld is an experimental platform for studying command and control (C2) by a team of distributed subjects in the context of firefighting command [1]. HGA is a method for analyzing cognitive systems consisting of multiple subjects.

Results: Applying HGA to C3Fire, we derived a list of variables associated with each goal. The variables provided additional measures of team performance closely related to the specific decisions subjects made while engaged in pursuing that goal. We conducted an upward flow analysis to identify situations where a subject assigned to a higher-level goal required feedback from a subject assigned to a lower-level goal. We also conducted a stability analysis to identify situations where two subjects were responsible for controlling the same variable simultaneously, thus creating a source of instability (i.e., potential for goal conflict) in the system.

Significance: The goal hierarchy and the associated list of controlled variables derived from HGA provided a new framework for testing optimality of subjects' decisions in the microworld-based experiments. Upward flow and stability analyses revealed potential ways to improve the distributed team performance by 1) enabling or supporting feedback between subjects where required, or 2) de-conflicting subject actions where required. The ability to assess the optimality of decisions made by human subjects is particularly important in the stochastic, non-linear dynamic decision making context of microworlds, where the traditional measures of human performance are not tuned to analyze series of decisions made by subjects where the merit of later decisions are dependent on earlier decisions, and where the merit of one subject's decisions are dependent on the decisions of other distributed team members. Finally, the goal templates we derived contained all necessary specifications needed to develop a computational model of distributed team performance.

Future plans: Our short-term plan is to use the HGA goal templates as the basis for developing a task network simulation of subject performance using the Integrated Performance Modelling Environment (IPME). The HGA-based IPME model will generate quantitative predictions of performance that will be validated against data from past or future microworld-based, human-in-the-loop experiments.

Sommaire

Hierarchical Goal Analysis of dynamic decision making in microworld experiments:

Zotov, Vlad; Chow, Renee; DRDC Toronto TM 2008-211; R et D pour la Défense Canada – Toronto; août 2009(c

Contexte: Les Forces canadiennes (FC) participent à des opérations nationales et internationales qui exigent une coordination avec leurs alliés, les organisations non gouvernementales et d’autres groupes qui sont souvent dispersés sur un vaste territoire. Une approche scientifique de l’analyse du rendement des équipes ainsi réparties est importante pour la mise au point de nouveaux outils ou de processus pouvant améliorer le rendement des équipes réparties. Une telle approche doit inclure des moyens permettant de déterminer quels sont les niveaux de rendement que doivent posséder les équipes, elle doit permettre d’observer le rendement réel et comparer ceux-ci au rendement nécessaire afin d’évaluer où et comment il est possible d’apporter des améliorations. Afin de mettre en valeur le rendement nécessaire, il nous faut savoir ce qui constitue une décision optimale dans les conditions dans lesquelles les sujets réalisent leur tâche. Par conséquent, nous devons disposer a) d’une plateforme expérimentale qui permet de saisir les caractéristiques importantes des dynamiques réelles de l’équipe, et b) d’une méthode permettant l’analyse du rendement des équipes réparties lors de la réalisation d’une tâche de ce genre.

Afin d’atteindre nos objectifs, nous avons analysé le rendement des équipes réparties dans le contexte d’une plateforme expérimentale C^3Fire (C^3 signifie « commandement, contrôle et communication ») par l’utilisation de l’analyse des buts hiérarchiques (ABH) Le micromonde C^3Fire est une plateforme expérimentale conçue pour permettre l’étude du commandement et contrôle (C2) exercé par une équipe de sujets répartis, dans le contexte d’un commandement de lutte contre les incendies. L’ABH est une méthode d’analyse des systèmes cognitifs constitués de plusieurs sujets.

Résultats : En appliquant l’ABH au C3Fire, nous en avons tiré une liste de variables associées à chaque but. Ces variables ont fourni des mesures additionnelles du rendement de l’équipe étroitement liées aux décisions particulières prises par les sujets alors qu’ils travaillaient à atteindre ce but. Nous avons effectué une analyse du cheminement ascendant de l’information afin d’identifier les situations où un sujet affecté à un but hiérarchiquement plus élevé a demandé une rétroaction à un sujet affecté à un but hiérarchiquement moins élevé. Nous avons aussi effectué une analyse de stabilité afin d’identifier les situations où deux sujets avaient pour tâche de contrôler simultanément la même variable, créant ainsi une source d’instabilité (c.-à-d., la possibilité de créer conflit entre les buts) dans le système.

Portée : La hiérarchie des buts et la liste associée des variables contrôlées tirées de l’ABH a permis d’obtenir un nouveau cadre pour tester l’optimalité des décisions des sujets dans les expériences basées sur les micromondes. Les analyses du cheminement ascendant de l’information et de la stabilité ont permis de découvrir de nouvelles façons d’améliorer le rendement des équipes réparties en 1) permettant ou en appuyant les échanges entre les sujets lorsque nécessaire, ou 2) dénouer au besoin les conflits entre les mesures proposées par les sujets. La capacité d’évaluer l’optimalité des décisions prises par les sujets humains est particulièrement

importante dans le contexte stochastique de la dynamique non linéaire de la prise de décisions dans les micromondes, un contexte où les mesures traditionnelles du rendement humain ne sont pas conçues pour analyser une série de décisions prises par des sujets lorsque la valeur des décisions ultérieures dépend de décisions antérieures, et où la valeur des décisions d’un sujet dépend des décisions prises par les membres de son équipe qui se trouvent à d’autres endroits. Finalement, les modèles de buts que nous avons obtenus contiennent toutes les caractéristiques nécessaires à la mise au point d’un modèle computationnel du rendement des équipes réparties.

Recherches futures : Notre plan à court terme vise à utiliser les modèles de buts de l’ABH comme base de mise au point de simulation du rendement des sujets dans un réseau de tâches en utilisant un environnement intégré de modélisation du rendement (EIMP). Nous espérons que le modèle d’EIMP basé sur l’ABH permettra de produire des prédictions quantitatives qui pourront être validées en les comparant à des données provenant d’expériences passées ou à venir de boucle de chaînons humains dans les micromondes.

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1 Introduction

The Canadian Forces (CF) are engaged in domestic and international operations that require co-ordination within and between its own elements (e.g., navy, land, and air forces) as well as with allies, non-government organizations, and other groups. This interoperability requires geographically dispersed people with different specialties, skills, cultural backgrounds, and levels of authority, to work effectively as a team. A scientific approach to analyze distributed team performance is important for developing new tools or processes to improve the effectiveness of distributed teams. Such an approach needs to include means of identifying required levels of team performance, observing actual performance, and comparing actual performance to required performance to identify where and how improvements may be made.

Team research literature separates team measures into two dimensions: 1) processes versus outcomes, and 2) team vs. individual [3]. Cannon-Bowers and Salas [4][3] formalized these distinctions by developing a framework for studying team performance. Figure 1 summarizes the view of Cannon-Bowers and Salas by outlining the relevant techniques for measurement in each of the possible combinations of dimensions: 1) team processes, 2) team outcomes, 3) individual processes, and 4) individual outcomes.

	TEAM	INDIVIDUAL
PROCESS	• Observational Scales • Expert Ratings • Content Analysis • Protocol Analysis	• Decision Analysis • Policy Capturing • Protocol Analysis • Observational Scales
OUTCOME	• Observational Scales • Expert Ratings • Critical Incidents • Automated Performance Recording	• Automated Performance Recording • Critical Incidents • Expert Ratings • Archival Records

Figure 1. Measurement tools useful to assess team performance. Adapted from Cannon-Bowers & Salas [3].

To enhance the inventory of team measurement techniques we used Hierarchical Goal Analysis (HGA)—a method to define the required levels of team performance using goals as the main units of analysis [2]. The method is based on Perceptual Control Theory (PCT) [4]. According to PCT, human behaviour is characterized as a perceptually driven system responding to discrepancies between perceived states of the external world and goal states. The system reacts to these discrepancies by trying to reduce them. The goals are the reference points for perception and control in the system. The process of goal decomposition is a process of identification of the current points of perceptual reference, beginning with the top-level goal and then descending into the lower levels. According to Powers[4], the process of descending is equivalent to asking the question how a person must behave in order to achieve a goal. Likewise, the process of ascending is equivalent to asking the question why a person is behaving in a certain way. The process of goal decomposition is similar to one used in the Means Ends Analysis (MEA) [5], where an action is chosen that will reduce the difference between current state and a goal state. The action is performed on the current state to produce a new state, and the process is recursively applied to this new state and the goal state. In contrast to the MEA process, which relies on explicit knowledge of problem space represented in the difference-subject tables (and, as such, it is an analysis of the environment), HGA decomposition analyzes interaction of the human with the environment in a real-time.

Unlike many other methods described in Figure 1, HGA aims to analyze a cognitive system that includes both subject's cognition and the environment in which they act. Distributed teams often operate in a complex and dynamic environment, making the context to be a part of the system they operate in [5]. Simon illustrated the role of complex environment on behaviour of live organisms in his famous ant's parabola. Consider the complicated movements and trajectories of an ant on the beach that might suggest the equally sophisticated internal mechanisms involved in the ant's navigation. In reality, however, the ant's path is mostly a reflection of beach complexity and its trajectory emerges from the interaction of the ant with its environment rather than from the internal mechanisms alone. One implication of this metaphor is that context-free analysis of human cognition will not be comprehensive. HGA offers the evaluation of the dynamics of subject's actions and specific requirements for interactions between subjects in *the context* in which they operate. These requirements can be compared against observed data to evaluate the performance of subjects. Taking into account that goals in HGA drive human actions both individually and collectively, the method can contribute to both team and individual measures outlined in Figure 1. At the same time, the HGA's focus on goals as desired states and on the process of achieving these goals allows it to contribute to both process and outcome measures in Figure 1.

To apply HGA to a distributed team of subjects, we turned to microworld-based experiments as they provide simulated interactive models of real world tasks that capture the high-level dynamics of subjects' actions while ignoring unnecessary detail [1][6][7]. Microworld-based experiments also allow experimenters to collect rich data related to subjects' decisions and actions. We selected the C^3Fire experimental platform [1] as it was specifically designed for investigating distributed team dynamics. It has been used by defence researchers in Canada [8][9] and abroad [1][6] for experiments on the impact of time pressure, team structure, and other factors on the performance of distributed command and control (C2) teams. Before we provide a detailed description of HGA, we will briefly describe the C^3Fire microworld and the C^3Fire-based experiment that we used as the basis of our analysis.

2 Microworld-based experiments

2.1 What is a microworld?

The term “microworld” suggests a miniature copy of the real world. This characterization captures important characteristics of a microworld: it is an abstraction of the real world that attempts to replicate features that are important to the decision-making process without replicating the real world environment. Microworlds include some important characteristics of the real system, that are selected and simulated in a relatively small and well-controlled model [7]:

Complexity. Microworlds are complex in the sense that subjects are faced with multiple, often-contradictory choices, forcing them to make trade-offs. Consider a microworld in which subjects need to co-ordinate their efforts to fight forest fires, but their resources to fight fires are limited, forcing subjects to re-evaluate their goals and to re-distribute their resources. There are some long-term consequences of that decision that might not be apparent immediately. For example, if the distribution of fire-fighting forces is not optimal, the fire may get out of control and overwhelm the capacity of fire fighters.

Dynamics. Microworlds are dynamic in the sense that the current state of the system at time t_n is a function of the previous state of the system at time t_{n-1} and so forth. These past effects are consequences of both subject actions and autonomous microworld properties. In our fire-fighting example, the current state of a forest fire will depend on the previous state of the fire and subjects’ actions at the previous moment.

Opaqueness. Microworlds are opaque in the sense that some aspects of the system are either “hidden” or “partially observed”. For example, the rate of fire spreading is not readily observable and can only be inferred by subjects after participating in fire-fighting activities.

The nature of decisions that subjects face in microworlds is often characterized as dynamic decision-making (DDM). Edwards [10] pointed out that DDM has a number of important features:

a. A series of decisions are necessary.

b. These decisions are interdependent (i.e., the decision made at time ti+1 depends on the decision made at time ti).

c. The environment changes both autonomously and as a function of the decision maker’s actions.

The complex, dynamic and opaque characteristics of microworlds make them similar to the cognitive tasks that people experience in the real world and it is expected that the microworlds provide a greater degree of experimental control. For example, the experimental scenario is under the experimenter’s control, subjects’ actions are recorded, time can be compressed, and the sequence of events can be repeated [9]. This ability of microworlds to create a well-controlled system that has important properties of the real world makes them an attractive option for

experimental tasks. The use of microworlds provides scientists with a tool to conduct experimental research within the dynamic, complex decision-making situations that characterize real-world environments (for a review see [7]). Moreover, it becomes possible to observe a team of subjects working with the same system, thus allowing observations of personal interactions and communications under controlled conditions.

Nevertheless, these very benefits of the microworlds that we outlined above impose some limitations on experimental control that otherwise would be available in a standard laboratory experiment. For example, the subjects in microworld-based experiments are active agents who direct and control the unique trajectory that unfolds during their participation in microworld-based experiments. Consequently, the traditional methods of assessment of subject performance (such as accuracy rates, time to complete task, relation between stimuli and responses) are not as directly related to subjects' decisions as they are in standard experiments [9]. Little is known about the cognitive demands associated with dynamic decision-making and the cognitive abilities required for decision-makers to be successful in a dynamic microworld. These shortcomings are associated with a lack of normative models that can characterize both optimal decisions and actions of subjects and that can be used as a benchmark to analyze observed performance. Our goal was to test HGA as a candidate that would capture the subject actions and create a goal hierarchy that would approximate optimal decisions under the circumstances.

2.2 C^{3}Fire

As we mentioned earlier, the C^{3}Fire microworld was used as our platform in order to analyze a cognitive system of distributed teams and the environment in which they operate. C^{3}Fire is a command, control, and communication simulation environment for analyzing, training, and experimentation of distributed decision-making [1]. The C^{3}Fire microworld is a fire-fighting scenario that requires subjects to make decisions on allocation of limited resources to control and extinguish the fire.

There are three classes of units in C^{3}Fire that subjects control: fire fighters (FF), water trucks (WT), and reconnaissance teams (RT). All units are interdependent so that success of the operation depends on coordinated efforts of different types of units. For example, WT units supply FF units with water and RT units search for new fire and provide fire-related information to other types of units. The type(s) of units that each subject controls is specified in the C^{3}Fire configuration file. The subjects can communicate through text messages with all other subjects (they can send a message to one or all other subjects). Every event in an experimental trial generates time-stamped data that C^{3}Fire automatically records and stores.

The C^{3}Fire microworld runs in a client-server configuration, meaning that each subject working in the simulation works at his/her own PC. Their actions are logged in the C^{3}Fire server and can be observed by a researcher who manages the experiment.

The terrain in the C^{3}Fire microworld is represented by a square matrix of 40x40 cells. The matrix represents an area that consists of five interacting simulation layers:

- A map layer, which is a background image that represents the area.
- A geographical object layer, consisting of different types of vegetation and houses.

- A fire layer, representing the state(s) of fire(s). The fires' start positions are determined in the session configuration file, but how the simulation develops depends on the fire's location, its proximity to different types of objects, wind properties, and subject actions. As a fire develops, each cell in the map can be in one of four states: clear, on fire, closed-out (i.e., by an FF), or burned-out (i.e., without intervention by an FF).
- A wind layer, representing the strength and direction of wind. Spreading of fires is influenced by the wind: when the wind is strong, the fire spreads faster in the wind direction. Wind speed and direction are defined in the scenario configuration file.
- A units' layer, representing different types of units with different functions that subjects can control. As we mentioned, there are three unit classes in C3Fire: FF units that fight fires, WT units that supply FF units with water, and RT units that search for new fires.

During simulation, subjects can see geographical objects and the locations of units they control. The fires and the units controlled by other subjects, however, are visible only when they are in close proximity to the unit that the subject controls. Typically, a visible area (or a "visual field") is set to a 3x3 or 5x5 square centered on the unit. Once a fire is within the visual field of the unit, it becomes visible. The fire remains visible even if the unit is moved away from that fire. The same detect-once mechanism is applied to the units controlled by other subjects that enter the visual field of the first subject. The ability of teammates to see each other's units and fires persistently once they are detected serves to imitate a state of established communication and a fire being mapped.

The C^3Fire microworld has been used extensively in previous research on network based command and control [1][6][8], and it originates from a long tradition of microworld research on distributed decision making [7].

2.3 C3Fire-based, distributed team experiment

To test the utility of HGA in the distributed team environment of C^3Fire, we needed an experimental task that would require subjects to co-operate in order to achieve their objectives. A previous experiment conducted by Jobidon et al. [8] met our requirements: it used the C^3Fire experimental platform and tested teams of either interdependent or independent subjects. Jobidon et al. compared two types of command structures—divisional (territory-specific) and functional (role-specific). In the divisional condition, each subject was assigned to one territory and controlled the same types of units in their territory: each subject controlled two FF units, one WT unit, and one RT unit. As a result, the success of the mission did not depend on co-operation between subjects. In the functional condition, by contrast, subjects controlled different types of units in a shared territory: the first subject (Operator 1) controlled four FF units and the second subject (Operator 2) controlled two WT units and two RT units. The success of the mission was highly dependent on the co-operation between subjects. The team performance was tested in a condition of sudden and unexpected change in the task workload: a new fire prompted subjects to re-distribute resources and to fight fires in more than one place.

This experiment produced many important findings related to team performance using standard performance measures (e.g., number of fire cells extinguished, time to detect a fire, total inactive time of each unit, etc.). Nevertheless, it is not clear how to evaluate the effectiveness of decision-

making process in the above conditions with a limited set of team performance measures. What is a normative model that can be used to benchmark the subjects' performance? How do we analyze the cognitive system of C^3Fire? Our goal was to answer these questions by conducting a HGA of the C^3Fire experiment.

3 HGA of C^{3}Fire

3.1 HGA of functional and divisional teams in C^{3}Fire

3.1.1 Goal hierarchy and controlled variables

The initial step in the analysis was to familiarize ourselves with the scenario and conditions used in Jobidon et al.'s [8] study. The familiarization was necessary to learn what actions and strategies of subjects would generate the best performance. To do so, the primary author evaluated the C^{3}Fire scenarios presented to both functional and divisional teams by re-playing some of the recorded experimental sessions and by running the experimental sessions using the same scenario used in Jobidon et al.'s [8] experiments. When the C^{3}Fire task was familiar enough, we progressed to the next stage of deriving and decomposing goals.

In HGA, the phrase "I want to perceive that" is considered to precede each goal description and helps to define the scope of perception. (For the sake of brevity, the phrase "I want to perceive that" will be replaced by "…" in all subsequent goal descriptions.) When the scope of perception (or the reference point for perception) is clear, then the goal that the subject wants to achieve becomes transparent. Our goal derivation process started with identification of the most general, inclusive goal that defined the overall objective of the C^{3}Fire system, regardless of how many subjects were in the experiment and how responsibility was divided between these subjects. This overall goal was "… Area is safe". In other words, the subjects want to perceive that the area is free of fires. If a fire is perceived, then there would be a discrepancy between the desired (or goal) state and the perceived (or actual) state of the world. Consequently, control action(s) would be needed to reduce that discrepancy (i.e., to correct the error). The perception and extinction of fires forms a feedback control loop, and the controlled variable for this loop is the number of fires.

After defining the main goal, we derived lower level goals by asking the questions of what further perceptions (and therefore control actions) are needed if the higher level goal is not perceived as met. In our "...Area is safe" example, if the subject perceives directly that the entire area is safe, then there is no need to direct attention to any sub-goal. Otherwise, the subject's attention would need to shift to a sub-goal that might or might not be sufficient on its own to support the higher-level goal. For example, to perceive that the area is free of fires, the subject needs to perceive that the whole area has been searched; thus, "… Area is searched" is a reasonable sub-goal, and the controlled variable associated with this goal may be "percent of area searched". Once a subject perceives that the whole area is searched, his/her attention may be re-directed upwards to the higher level goal of "… Area is safe".

To continue with the goal decomposition, we noted that the "… Area is searched" sub-goal is not sufficient on its own to support the "… Area is safe" higher-level goal. Specifically, when the area is not safe (i.e., number of fires >= 1), even though the whole area may have been searched, there are additional sub-goals that may demand the subject's attention, including: "… Fire is prioritized" for each of the fires and "… Fire is extinguished" for each of the fires. The "… Fire is prioritized" sub-goal can be associated with a controlled variable "fire priority" (which may range from 1 to n, assuming there are n fires). The "…Fire is extinguished" sub-goal can be associated

with a controlled variable "fire state" (which may have the values of active, burned-out, or put-out). It is only when each fire has been prioritized, and each fire has been extinguished that it becomes possible for the higher-level goal of "…Area is safe" to be achieved. However, as long as the search for fires, the prioritization of fires, and the extinction of fires continue to occur, steps are being taken to reduce the error associated with the overall goal of "…Area is safe" and to bring it closer to achievement.

In an HGA, a controlled variable is defined for each goal in the hierarchy. Depending on the goals, these controlled variables can be of different types. For example, for the goal "… WT established visual contact with FF", the controlled variable is whether visual contact has been established or not, thus the variable is binary. The variable type can also be an integer (e.g., number of units searching for fast-burning fire), a real number (e.g., fire acceleration rate), or an array of numbers (e.g., number of fire cells at each fire).

We continued with the goal decomposition process until the lowest level of control was reached. In microworlds, the terminal goals are usually restricted by the resolution of the simulation. Consider the goal "… Units en route to assigned destinations". In C^3Fire, once units are sent to specific locations, the units' movements come under simulation control, so no more action from subjects is possible or required. Therefore, there is no reason to further decompose the goal.

After identifying and mapping all goals, both authors evaluated the complete goal hierarchy to detect and eliminate any redundant goals, modify goals, add missing goals, and re-position or re-connect goals in the different parts of the hierarchy. Figure 1 shows part of the C^3Fire goal hierarchy related to search and fire detection activities, while Figure 2 shows part of the goal hierarchy related to fire-fighting activities. Note that Figures 1 and 2 display different parts of the same goal hierarchy. Connections between goals show paths along which subjects can direct attention (e.g., from higher to lower level and vice versa) while controlling the system. The depth of the goal hierarchy varied from three to six levels. In addition to information displayed in Figures 1 and 2 (goal number and description), Appendix A shows the controlled variable for each goal.

3.1.2 Assignment of subjects

The next step in the analysis was to assign subjects to goals. With a few exceptions, this process was determined by experimental conditions that specify the roles of each subject outlined in the configuration file of the C^3Fire microworld. Recall that in the functional condition of Jobidon et al.'s [8] experiment, one subject controlled four FF units and the other subject controlled two WT units and two RT units. Accordingly, if the controlled variable of a goal was related to fire-fighting activities, than the first subject would be assigned to that goal, and if the controlled variable of a goal was related to water supplying and reconnaissance activities, then the second subject would be assigned. There are cases where either subject can achieve a goal. Consider the "… Area is searched" goal: before the fire location is detected, both subjects can send their units to search for fires since FF units and WT units are also capable of detecting a fire in their vicinity. However, a goal is generally assigned to the subject who is ultimately responsible for the goal. In the specific example of "… Area is searched", we assigned that goal to Operator 2 who controlled the RT units. In the divisional condition of Jobidon et al.'s experiment [8], each subject was responsible for a territory while controlling the same variety and numbers of units as the subject. Therefore, both subjects in this condition had identical assignments. The last four columns of

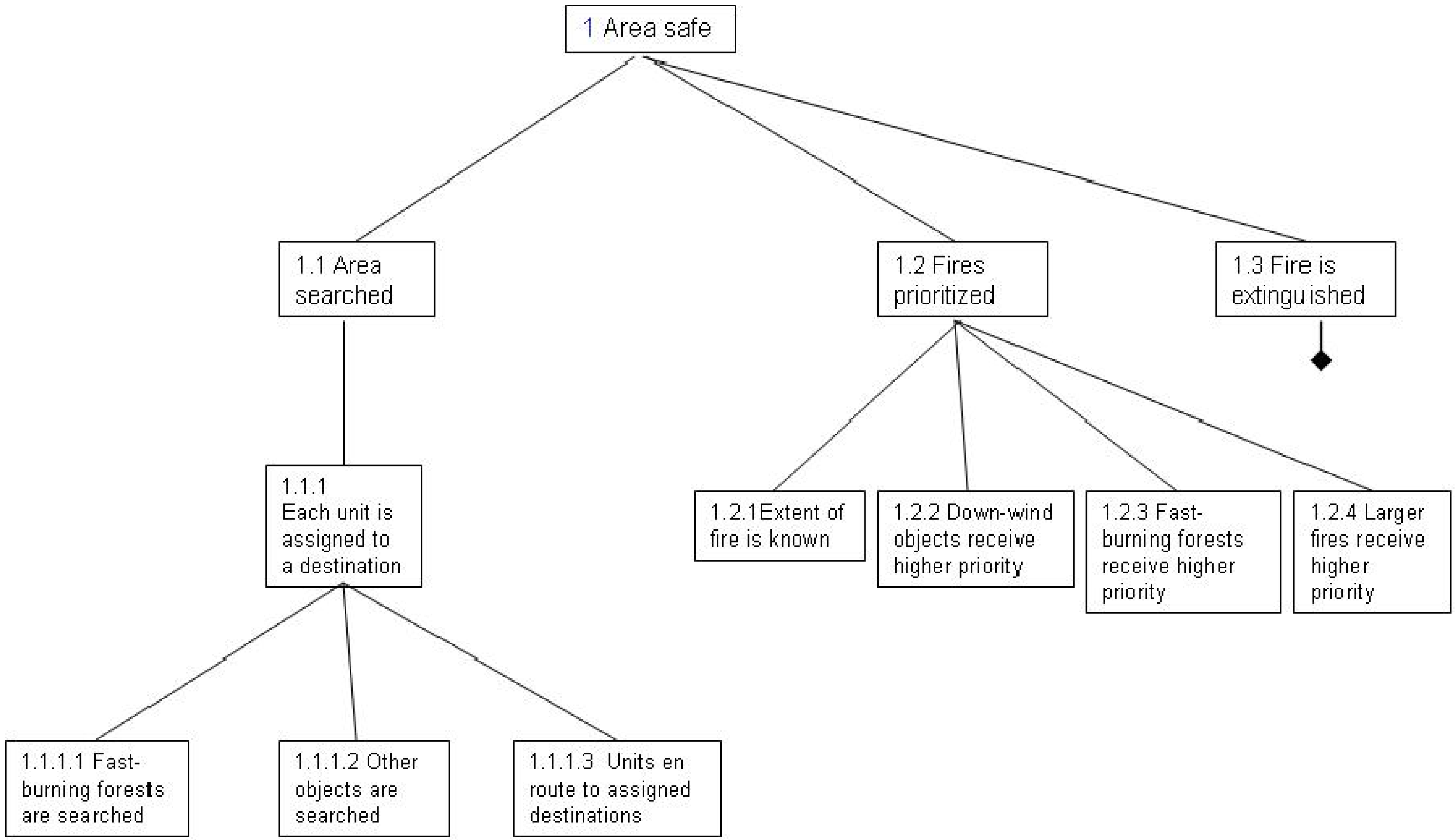

Figure 1. First part of the goal hierarchy. Filled diamond indicated a hidden part of tree (shown in the next figure)

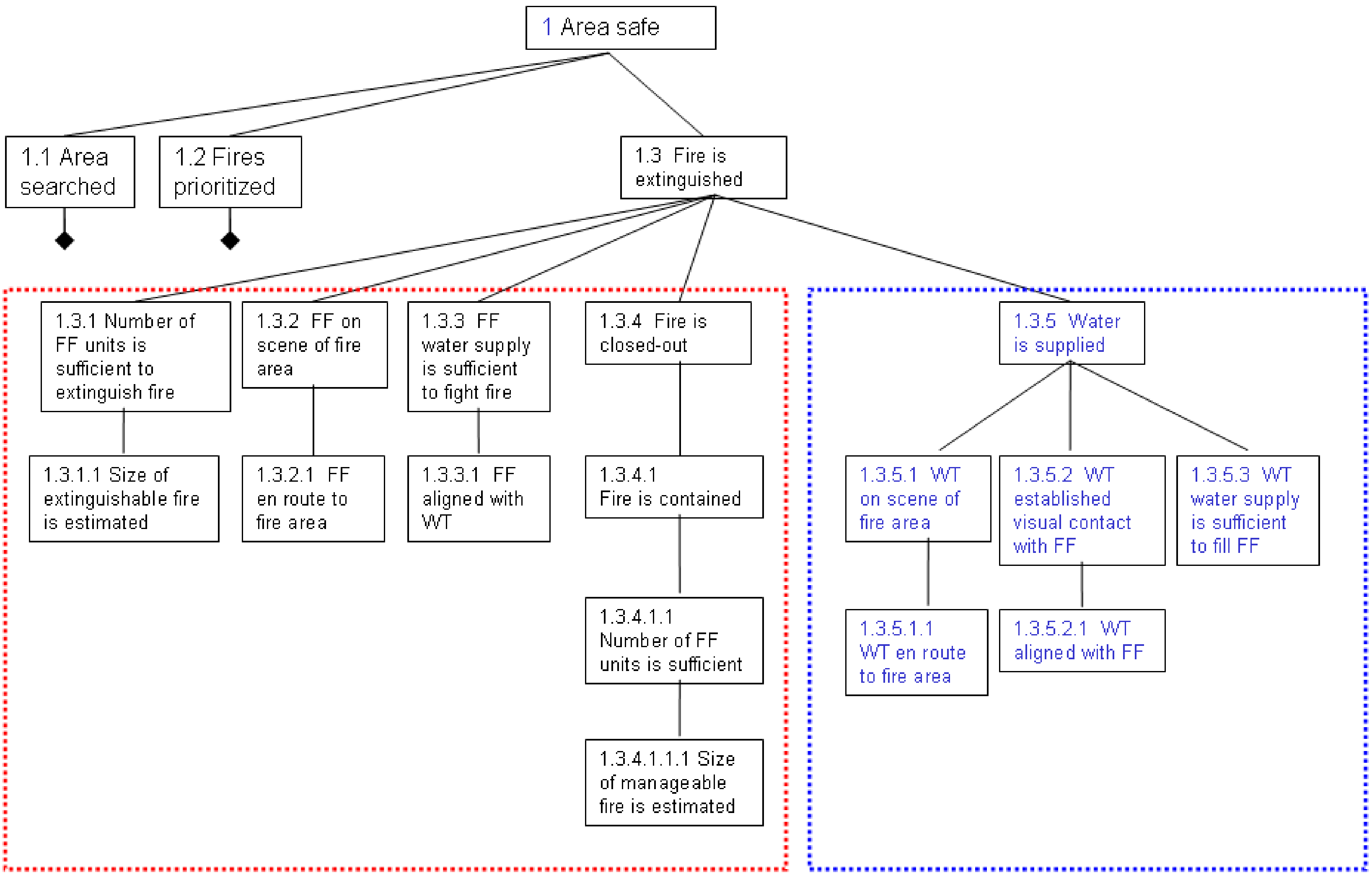

Figure 2. Second part of the hierarchy. The left red-dotted area demarcates a fire-fighting activities while right blue-dotted area represents water-supplying activity.

Assigned Operator	HUMAN				WORLD
1	INPUT	CENTRAL PROCESSING	OUTPUT		
Goal:	**Required Knowledge states**	**Perceptual/ Cognitive processes**	**Ending conditions**	**Ending effects**	**Influenced Variable(s) (External)**
1.1.1 Each unit is assigned to destination	**Declarative:** **General guidelines for assigning units to fires based on units' capabilities:** -speed of movement; -time to extinguish fire; -water supply required to sustain fire-fighting (WT) **Situational:** **Situation assesment:** -fire extent and shape of fire, -location of houses relative to wind direction, -location of forests relative to wind direction, -number of units available, -distance from fire(s) to nearest unit(s) **Information updates between O1 & O2: (Functional condition only)** -current locations of units, -assigned locations	**Visual** -central; **Cognitive** -spatial pattern recognition; -reasoning **NON-IPME categories** -memory (Memorization)	D_{xy} set for all units;		EV1: --- $D_{x,y}$ (Assignments of each unit FF_j, WT_k, & RT_m to a destination)
	Initiating conditions	**LIST OF IPME TASKS**	**Influenced Variable(s) (Internal)**		**NOTES**
	D_{xy} is not set	* AssignTagToUnit; * GetUnitCoordinate; * AllocateUnit	Status of units assignments		Once assignments are completed, operators concentrate on monitoring of fire-figting and recon info

Figure 3. Goal template for goal 1.1.1 “Each unit is assigned to destination”.

Annex A shows subject assignments for the goals in the functional versus divisional conditions. For the divisional condition, subscript is used to indicate the type of unit the assigned subject used to achieve that goal.

3.1.3 Goal templates

The next step was to fill out all the fields in the goal template for each goal (Annex B). The goal template is adapted from examples shown in Hendy et al. [2]. The templates are based on PCT, which models human behaviour as a perceptually driven feedback control system [4]. Each template consists of the following fields in addition to the goal number, goal description, and the assigned subject(s):

- initiating conditions that prompt a subject to attend to this goal;
- required knowledge (both declarative and situational) to achieve the goal;
- perceptual and cognitive processes involved in achieving the goal (Note: this field was intended to support the development of a discrete event simulation of subject behaviour using the IPME software. The software can model competition for limited cognitive resources and outline what perceptual or cognitive processes are active at a given time);
- list of tasks to be performed on the system to achieve the goal (Note: this field was also intended to support the development of a discrete event simulation of subject behaviour using the IPME software);
- ending conditions that specify the goal completion criteria and prompt a subject to direct attention away from this goal;
- ending effects that occur when the goal is achieved;
- internal influenced variable(s) (i.e., belief or knowledge state(s)s held by the subject) that get(s) updated when the subject attends to this goal; and
- external influenced variable(s) (i.e., state(s) of the world) controlled by the subject in attempt to achieve this goal (Note: The term "influenced variable" is used as a synonym for the term "controlled variable" which had been introduced earlier in this report. Some researchers feel that not all variables can be controlled directly by subjects, so it is more appropriate to describe the variables as being "influenced" by the subject using an interface).

The format of the template is intended to reflect the mechanisms of the PCT loop. All but the last fields describe what occurs within the human cognitive system, while the last field describes what occurs in the world with which the human cognitive system interacts. Figure 3 shows an example of a filled out template for the goal "Each unit is assigned to destination". Annex B shows the goal templates for all goals in the C^3Fire hierarchy.

3.2 HGA-derived methods of performance analysis

The completion of the goal templates concluded the process of HGA. Our next step was to evaluate the benefits that HGA brings to the analysis of distributed team performance. We

concentrated on three analyses that HGA offers to enhance team performance measures: the analysis of the HGA-derived controlled variables to measure team performance, upward flow analysis, and stability analysis.

3.2.1 Controlled variables in HGA

Recall that the analysis of Jobidon et al.'s experiment [3] included a limited number of performance measures, as shown in the second column of the Table 1. Some of these variables, such as number of cells extinguished or the number of burned cells, serve as general measures of team performance and provide a good overall picture of subjects' performance. At the same time, these measures are not closely related to a specific goal that subjects were engaged in achieving. Neither are they tuned to a specific decision that subjects made, making these general measures hard to use to evaluate the decisional errors that subjects make.

As we noted earlier, in the dynamic environment of microworld-based experiments, it is difficult to specify a normative action that would be the most appropriate subject response under circumstances he or she is in. The controlled variables derived for each goal in the HGA hierarchy suggest measures of performance that are closely related to a specific decision in the process of achieving a particular goal. The third column of Table 1 lists the HGA-derived controlled variables (see Annex A for a detailed description of the variables in the goal templates) and the fourth column lists the corresponding measure of performance that was derived out of these controlled variables and that can be used as dependent variables in the analysis of subject's performance.

Let us assume that the subjects allocated most of their units to the same quadrant, while ignoring other areas. At this moment in time, there may be no negative effect on the team's performance in terms of conventional measures like number of burned cells or number of extinguished cells. Depending on where the next fire ends up occurring (e.g., within or outside the quadrant where

Table 1. List of measures in Jobidon et al.

Var. number	Measures used in Jobidon et al.	Converted measure of performance
1	Number of burnt cells	N/A[1]
2	Number of extinguished cells	N/A
3	Time to detect second fire	Units spread index
4	Communication frequency	Proportion of time units were idling

[1] No conversion is necessary; the variable can be applied as is.

Table 2. List of measures derived from HGA

Var. number	Controlled variables derived form HGA	Converted measure of performance
1	Number of fires	N/A
2	Percentage of area searched	N/A
3	Assignment of each unit to a destination	Units spread index
4	Number of units searching for fire (fast-burning fire)	Proportion of time units were idling
5	Number of units searching for fire (non fast-burning fire)	Proportion of time units were idling
6	Number of units en route to a destination	Proportion of units en route to a destination
7	Priority of fire	Number of engaged units at each fire
8	Extent of fire	Proportion of burning cells detected
9	Number of burning cells at fire F_i	N/A
10	Number of FF units fighting fire	N/A
11	Number of FF units on scene	N/A
12	Number of FF units en route	Proportion of FF units en route to a destination
13	Number of burning cells without barrier	N/A
14	Fire acceleration rate at fire F_i	N/A
15	Number of FF units fighting fire	Proportion of FF units fighting fire
16	Number of WT units assigned to each fire	N/A
17	Number of WT units on scene	N/A
18	Number of WT units en route to fire	Proportion of WT units en route to a destination
19	Number of WT units established visual contact with FF units	N/A
20	Quantity of water each WT has	N/A

most of this subject's units have been assigned), there may also be no negative effect (or even a positive effect) on the other conventional measure of time to detect second fire. In the long-term, however, this decision should still be considered sub-optimal because it would lead to the delays in detecting new fires (if multiple subsequent fires were to occur and they were to be evenly distributed throughout the area), putting subjects in a situation where they might not have

sufficient resources to fight fires. Therefore, instead of relying only on a single variable (e.g., the number of burned cells), it may be beneficial to define new HGA-based measures of performance related to unit assignments. For example, some possible ways to evaluate and compare unit assignments include:

- Total amount of time that the units were left idle (i.e., unassigned to any destination), where a shorter time would be indicative of superior performance.
- Average distance between the FF units' assigned destinations, where a larger distance would be indicative of superior performance (i.e., "Units spread index" in Table 2).

Other HGA-derived controlled variables such as "percentage of area searched" (e.g., over the course of the trial or in each time block), "number of units searching for fire in fast-burning forests" (e.g., averaged across time) provide additional measures of performance that can be used to evaluate the various decisions made by subjects. These measures differ from the more conventional measures used by Jobidon et al. [3] in that they are not made or broken by prior decisions and stochastic elements of the microworld. That is, even if the subjects initially concentrated their units in one area, they could still re-distribute these units later on to attain reasonable overall levels of performance, without being severely penalized in terms of "time to detect second fire" if the second fire happened to occur very early in the trial or far away from the initial locations of their units.

The co-ordination between two subjects can also be evaluated in the context of these assignments to test if all necessary information related to units' location and actions were fully exchanged between two teammates. Recall that in the functional condition of the Jobidon et al. experiment the success of mission depended on co-ordination between teammates. Any omissions in information exchange would result in incomplete and outdated situational awareness of subjects. The HGA's controlled variables can be used to analyze the direct effect of impaired communication (e.g., information was not exchanged promptly) on team performance.

Obviously, not all of the HGA-derived controlled variables can contribute equally to the evaluation of subject's performance. For example, the controlled variable "Number of fires" for goal 1 "… Area is safe" is not tuned to trace any particular decision; rather, it reflects the overall performance of subjects. Some other controlled variables, such as "Fire acceleration rate at fire F_i" for goal 1.3.3.1 "… Number of FF units is sufficient to contain fire" might be hard to trace as the situation constantly changes; so while it should be possible to use a low fire acceleration rate as an indicator of good performance, the computational effort involved may be more difficult to justify, especially given the large number of other measures that are available and that appear easier to apply and interpret. Nevertheless, the majority of the HGA-derived controlled variables can enhance both performance and decision-making analyses.

Recent empirical evidence supported this claim. Zotov, Smith, & Chow [9] applied a subset of the controlled variables (Table 2) to their team-based experiment. The experiment investigated the impact of voice communications on distributed two-person teams in a simulated tactical-level dynamic environment of C3Fire. The type of voice communications allowed between subjects was manipulated in different communication conditions. Since the experiment was based on the same scenario and platform as one in Jobidon et al.'s experiment, Zotov et al. were able to analyze their data applying the same controlled variables that were reported in this work. When the standard measures (not derived from HGA) were used to analyze subject performance, the

results did not differ between conditions. However, when the HGA-derived controlled variables were applied, a marked deterioration was observed when subjects were only allowed voice communications between sessions. While these findings cannot be generalized directly to the Jobidon et al. experiment [8], considering the similarity in experimental design and the platform used in both studies, we expect to enhance team performance analysis by applying HGA-derived variables to Jobidon et al.'s data.

3.2.2 Upward flow and stability analyses

Two additional analyses are emergent from HGA: the analysis of upward flow of information required from subjects assigned to low level goals to subjects assigned to high level goals, and the analysis of system stability that examines potentially unstable situations caused by multiple subjects competing for control of common variables [2]. Upward flow analysis starts from the lowest level of the hierarchy and examines the upward links from each goal to its parent goal, and notes all cases where these two goals are assigned to different subjects – which translate into a requirement for one subject responsible for the supporting goal to the subject responsible for the supported goal at higher level. Stability analysis starts with the list of controlled variables for all goals in the hierarchy, and notes all cases where the same variable is assigned to multiple goals that are controlled by different subjects Once such an unstable situation (i.e., with the potential for goal conflict) is identified, recommendations for stable control can be offered.

3.2.2.1 Upward flow analysis

Recall that in the divisional condition of Jobidon et al.'s experiment [8], each subject controlled the same type of units as her teammate. Therefore, both subjects in this condition had identical assignments and there was no need to exchange information between teammates. Thus, for upward flow analysis, only the functional condition was evaluated. Table 3 lists situations in the functional condition of C^3Fire experiment [8], where information transfer was required between two subjects. These situations can be compared to actual communications between subjects in the experiment to see if the required information transfer was partial, delayed, or absent. The effectiveness of information transfer can be evaluated by analyzing the content of communication between two subjects. We anticipate that these failures to transfer required information to affect subjects' performance during workload transitions (e.g., when a new fire is detected). We can also examine the effects on performance if the required transfer does not occur.

There are several ways in which the results of the upward flow analysis can be applied to extend the findings of the Jobidon et al.'s [3] experiment. Recall that in [3], the only measure used to analyze communications between subjects was overall communication frequency, which can be compared between the two experimental conditions. As seen in Table 3, however, we can hypothesize that in the functional condition, there is a much stronger requirement for Operator 2 (responsible for the WT and RT units) to provide feedback to Operator 1 (responsible for the FF units), so it may be useful to examine the relation between the frequencies of communication by each subject and performance (e.g., perhaps only more communication by Operator 2 would be associated with superior performance), or between the ratio of communication frequencies by the two subjects and performance (e.g., perhaps a higher ratio of communications by Operator 2 to communications by Operator 1 would be associated with superior performance). Some indirect supporting evidence was demonstrated in Zotov et al.'s study [9], in which delays in sharing of

information between subjects in the non-verbal condition contributed to delays in fire-fighting activities and, consequently, contributed to inferior performance in this condition.

Table 3.Upward flow analysis results - Information flow required between subjects in Functional condition.

Parent Goal	Subject	Child Goal	Operator	Need for information flow
1 Area is safe	1	1.1 Area is searched	2	2→1
1.1 Area is searched	2	1.1.1 Each unit is assigned to destination	1	1→2
1.1.1 Each unit is assigned to destination	1	1.1.1.1 Areas with fast-burning forests are searched	2	2→1
1.1.1 Each unit is assigned to destination	1	1.1.1.2 Other objects are searched	2	2→1
1.1.1 Each unit is assigned to destination	1	1.1.1.3 Units en route to assigned destinations	2	2→1
1.1.2 Fires are prioritized	1	1.1.2.1 Each unit is assigned to destination	2	2→1
1.3 Fire is extinguished	1	1.3.1 Water supplied is available to fight each fire	2	2→1

3.2.2.2 Stability analysis

Due to the well-defined and distinctive roles that subjects play in the C^3Fire platform, sources of instability are rarely present. Table 4 lists two goals that have the same controlled variable, thus creating a potential for instability in the system. The situation occurs when both subjects are trying to align their units for water refilling, which can result in the multiple small re-adjustments of units before they are aligned and ready for refill. For example, in Zotov et al.'s study, teams in the no-verbal feedback condition spent considerably more time aligning each other's units, thus contributing to the inferior performance of this condition relative to the other conditions, in which immediate verbal feedback between subjects helped to co-ordinate alignment of units. Once the unstable situation is identified, the recommendations for stable control (e.g., training, system design) may be introduced to improve team performance. In the context of Zotov et al.'s study, subjects can be instructed with simple rules of unit alignment.

Table 4. Stability analysis results – Potential for goal conflicts in Functional condition.

<table>
<tr><th>Influenced variable</th><th>Operators</th><th>Goal</th><th>Potential for competing control</th><th>Recommendation for stable control</th></tr>
<tr><td rowspan="2">Units location</td><td>2, 1</td><td>1.3.3.1 FF units are aligned with WT units</td><td rowspan="2">Both subjects try to align their units simultaneously</td><td rowspan="2">Subjects should be instructed explicitly who is to stay stationary, and who is to align his/her units</td></tr>
<tr><td>2, 1</td><td>1.3.5.1.1 WT units are aligned with FF units</td></tr>
</table>

4 Summary and future plans

The stochastic, non-linear nature of events unfolding in a dynamic distributed decision field has a significant impact on human performance [7]. Subsequently, many standard measures of performance including both individual and team-based measures (e.g., time to complete task, error rate, or subject's workload) are often affected by environmental factors, obscuring the evaluation of subject's decisions. To analyze the cognitive system of the C^3Fire microworld, we used Hierarchical Goal Analysis [2] to analyze the subjects and the environment with which they interacted. The C^3Fire experimental platform provided a simulated interactive environment, in which team collaboration, interactions, shared situational awareness, and co-ordination can be analyzed and tested. Since C^3Fire microworld is a platform for running team-based experiments, we used a C^3Fire-based experiment as the basis for our cognitive analysis. We used Jobidon et al.'s experiments [8], which provided us with a set of parameters that specify subjects' assignments, scenario details, units' capabilities, and fire dynamics. The performance data (e.g., number of fire cells extinguished, time to detect a fire, total inactive time of each unit, etc.) and the ability of C^3Fire to re-play experimental sessions helped us to capture the subjects' actions and to infer corresponding goals.

The answer to the question of whether the cognitive system analysis we performed enhanced our ability to evaluate subjects' decision-making processes and the effect of their decisions on their performance is affirmative—by evaluating the cognitive system of C^3Fire, we successfully mapped the subjects' performance onto a corresponding goal structure that defined the expected performance in the dynamic system. The controlled variables associated with each goal provided additional measures of performance that were closely related to the specific decisions that subjects made. The upward flow analysis identified situations that required subjects to exchange information. The effectiveness of information transfer between subjects observed in the C^3Fire experiment can be tested relative to these specific communication requirements rather than relying on the coarser measure of overall communication frequency. The stability analysis revealed a situation when both subjects might need to control the same variable to achieve different goals, and pointed to possible interventions that may be introduced to improve team performance. Both upward flow and stability analyses can be used to supplement the analysis of team performance in a dynamic experiment such as C^3Fire, by suggesting a number of new conditions that may impact performance, and a number of new measures that may be used to evaluate performance.

We cannot state definitively that the goal structure we derived in conducting HGA is the normative model of subjects' performance in C^3Fire. On the one hand, HGA can serve as a guiding tool to pinpoint when specific decisions need to be made by subjects during the simulation. On the other hand, the optimality of the HGA-derived decisions is based on human (i.e., the analysts') evaluation of the subjects' performance. As such, the process cannot be free from subjectivity and, therefore, may not be a genuinely normative model of human performance. Additionally, the goal hierarchy provides a static representation of what is really a dynamic decision making process, thus, it cannot actually predict the subjects' performance across time.

Nevertheless, the goal templates (in Annex A) do outline the specifications for a dynamic simulation model that can be used to predict team performance and these predictions can be validated against experimental data. HGA's objective is to identify a goal and the way this

specific goal can be achieved (e.g., error-correction decision) rather than behaviour (e.g., error-correction steps). This focus on goals and decisions distinguishes HGA from other analytical methods that rely on human ratings that tend to be lacking diagnostic specificity [11]. In response to the limited utility of the human rating methods, a number of researchers have developed a number of event-based measurement methods that provide diagnostic capabilities for identifying specific problem areas [12][13][14][15]. We hope that HGA can be a useful addition to this group of methods that identify and capture team processes.

Besides our main objective to use HGA to enhance the evaluation of team performance in dynamic situations, the description of the way this HGA was conducted can serve as a guiding tool for researchers interested in conducting a cognitive analysis of distributed team performance. As mentioned in Hendy et al.'s work [2], the HGA method is not as intuitive as some traditional methods, and it requires more training and experience to master the method. We believe that our specific example will facilitate the process of mastering HGA.

4.1 Future plans: IPME model based on HGA

Our next step is to adapt the outputs of the HGA process (specifically the goal hierarchy and the completed goal templates) into an IPME task network to create a dynamic model of subjects' actions. IPME is an integrated suite of simulation and modeling tools designed to investigate systems that rely on human performance to succeed. As such, IPME provides a realistic representation of humans in complex environments, making it one of the best-suited platforms available designed to model team-based performance [11]. IPME consists of five major components (or sub-systems) that jointly represent a system: a task network model, a crew model, an environment model, a performance shaping function model, and an external communication model. IPME allows hierarchical representation of tasks, thus the HGA goal hierarchy can be translated quite readily into an IPME task network that preserves the goal structure we developed. Among IPME's features, we are primarily interested in its ability to analyze and predict subject's performance in a dynamic environment. Specifically, IPME offers workload measurement, analysis of errors, time series analysis, and the ability to test and run "what if" scenarios, thus saving time and effort required to run different experimental scenarios.

Additionally, IPME has a number of features that make it easier to integrate IPME with other simulations and models in a real-time environment. IPME's function library, user-defined functions, and an event catalogue allow dynamic events to trigger based on time or a condition within the simulation. These features would allow high fidelity testing of the properties of C^3Fire scenarios that we investigated and analyzed using HGA. Recall that in Jobidon et al.'s [8] experiments, the fire events were triggered by the scenario configuration file at specific moments during the experiment. Once a new fire is detected, the subjects respond by sending and re-allocating units to the fire. These are examples of time-triggered and condition-triggered events that IPME can simulate and predict.

The IPME model of C3Fire microworld can be validated against data from human-in-the-loop experiments. Considering that the model is based on goals rather than on tasks, we hope that the model can be generalized to other C^3Fire experiments with only a few changes related to subject assignments and scenario details.

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Annex A Controlled varaibles and assignment of subjects (operators)

Goal number	Goal/Subgoal	Controlled Variables (external)	Ending condition	Functional Team		Divisional Team	
				Assigned to Operator			
				1 (4 FF)	2 (2WT, 2RT)	1	2
						(2 FF, 1WT, 1RT)	
1	Area is safe	**Number of fires** (N_{fires})	$N_{fires} = 0$	X		X_{FF}	X_{FF}
1.1	*Area is searched*	**Percentage of area searched**	$Area_{searched(\%)} = 100$		X	X_{RT}	X_{RT}
1.1.1	Each unit is assigned to destination	**Assignments of each unit** (FF_j, WT_k, RT_m) **to a destination D(x,y)** (j = 1..4 FF units; k = 1..2 WT units; m = 1..2 RT units)	$D_{(x,y)}$ is set for all units	X		X_{FF}	X_{FF}
1.1.1.1	Areas with fast-burning forests are searched	**Number of units searching for fire in area X_{af}** (af = 1 to nf; nf is a number of areas with forests)	$X_{af} \geq 1$		X	X_{FF}	X_{FF}
1.1.1.2	Other objects are searched	**Number of units searching for fire in area X_{ah}** (ah = 1 to nh; nh is a number of areas with houses)	$X_{ah} \geq 1$		X	X_{RT}	X_{RT}
1.1.1.3	Units en route to assigned destinations	**Number of units en route to a destination ENR_{jkm}** (jkm = 1 to tu; tu is a total number of units j+k+m)	$ENR_{jkm} < 1$	X	X	X_{RT}	X_{RT}

Notes. FF is a fire-fighting unit, WT is a water-tank unit, and RT is a reconnaissance unit. For the divisional condition both subjects assigned to each goal; the assignments for this condition display what units a subject controls.

Goal number	Goal/Subgoal	Controlled Variables (external)	Ending condition	Functional Team		Divisional Team	
				Assigned to Operator			
				1 (4 FF)	2 (2WT, 2RT)	1	2 (2 FF, 1WT, 1RT)
1.2	*Fires are prioritized*	**PF**	**Priority of fire** (PF_1 = (x, y); (PF_1 is a fire with the highset priority; [x,y] is a fire's location)	X		X_{FF}	X_{FF}
1.2.1	Extent of fire is known	**Extent of fire** (EPi,xy) (Co-ordinates of border points outlying the extent of fire Fi; i = 1..N, N number of fires; xy a pair of co-ordinate outlying Fi; br = 1..4, br is border; four br pairs of xy define the most West, North, East, & South co-orditnes of each fire)	$EP_{i,xy}$ is set for all i		X	X_{RT}	X_{RT}
1.2.2	Fires adjacent to downwind objects receive higher priority	**PF**	**Priority of fires according to wind direction** (if PF_{di} is fire adjacent to a down-wind object and PF_{ui} is a fire adjecent to an up-wind object, then $PF_{di} < PF_{ui}$)	X		X_{FF}	X_{FF}
1.2.3	Fast-burning forests receive higher priority	**PF**	**Priority of fires according to type of forests** (if PF_{ffi} is a fast-buring forest and PF_{sfi} is a slow-buring forest, then $PF_{ffi} < PF_{sfi}$)	X		X_{FF}	X_{FF}
1.2.4	Larger fires receive higher priority	**PF**	**Priority of fires according to their sizes** (for two fires PF_{fi} and PF_{fj}, if size $F_i > F_j$ then $PF_{fi} < PF_{fj}$)	X		X_{FF}	X_{FF}

Goal number	Goal/Subgoal	Controlled Variables (external)	Ending condition	Functional Team Assigned to Operator		Divisional Team Assigned to Operator	
				1 (4 FF)	2 (2WT, 2RT)	1 (2 FF, 1WT, 1RT)	2
1.3	Fire extinguished	**Number of burning fire cells (S_i) at fire F_i** (i = 1..n; n is a number of fires)	S_i = 0 for all i's	X		X_{FF}	X_{FF}
1.3.1	Number of FF units is sufficient to extinguish fire	**Number of FF units fighting fire** (ENG_{hi})	$ENG_{hi} \geq S_i / FFE_i$ (-Si is a number of burning cells at fire Fi; -FFEi is a number of burning cells at fire Fi a single FF can extinguish; -FFEi / Si is number of units to extinguish the fire)	X		X_{FF}	X_{FF}
1.3.1.1	Size of extinguishable fire is estimated	**Number of burning cells at fire F_i a single FF unit can extinguish** (FFE_i)	FFE_i is set	X		X_{FF}	X_{FF}
1.3.2	FF on scene of fire area	**Number of FF units on scene (ENG_i)** (ENG_i; i = 1..h; h is number of fires)	$ENG_i \geq 1$ for all hi's	X		X_{FF}	X_{FF}
1.3.2.1	FF en route to fire area	**Number of FF units en route to fire (ENR_i).** (ENR_i; i = 1..h; h is number of fires)	$ENR_i \geq 1$ for all i's	X		X_{FF}	X_{FF}
1.3.3	FF water supply is sufficient to fight fire	**Quantitiy of water each FF_k has** (binary; full vs empty; k = 1 .. 4)	FFk = "full"	X		X_{FF}	X_{FF}
1.3.3.1	FF aligned with WT	**Alignment between FF and WT units** (UA)	UA = "aligned"	X		N/A	N/A
1.3.4	Fire is closed-out	**Number of burning cells without barrier** (XB_i)	XB_i = 0	X		X_{FF}	X_{FF}
1.3.4.1	Fire is contained	**Fire acceleration rate** (S_i-PS_i) **at fire F_i**	$S_i - PS_i \leq 0$ for all i's (S_i is a number of buring cells at fire F_i at time t; PS_i is a number of buring cells at fire F_i at time t-1)	X		X_{FF}	X_{FF}
1.3.4.1.1	Number of FF units is sufficient to contain fire	**Number of FF units fighting fire** (ENG_i)	$ENG_i = S_i / FFC_i$ (FFC_i x S_i is number of units needed to extinguish the fire)	X		X_{FF}	X_{FF}
1.3.4.1.1.1	Size of fire controlled by a single FF unit is estimated	**Number of burning cells at fire F_i a single FF unit can contain** (FFC_i)	FFC_i is set	X		X_{FF}	X_{FF}

Goal number	Goal/Subgoal	Controlled Variables (external)	Ending condition	Functional Team		Divisional Team	
				Assigned to Operator			
				1 (4 FF)	2 (2WT, 2RT)	1 (2 FF, 1WT, 1RT)	2
1.3.5	Water supplied is available to fight each fire	**Number of WT units assigned to each fire** (WT_i)	$WT_i \geq 1$ for all fires		X	X_{WT}	X_{WT}
1.3.5.1	WT unit on scene of fire area	**Number of WT units on scene ($WENG_i$)** ($WENG_i$; i = 1..h; h is number of fires)	$WENG_i \geq 1$ for all i's		X	X_{WT}	X_{WT}
1.3.5.1.1	WT unit en route to fire area	**Number of WT units en route to fire ($WENR_i$).** ($WENR_i$; i = 1..h; h is number of fires)	$WENR_i \geq 1$ for all i's		X	X_{WT}	X_{WT}
1.3.5.2	WT unit established visual contact with FF unit	**Number of WT units on scene that established visual contact with FF units** ($Vis\_WT\_FF_k$; k = 1 .. 2)	$Vis\_WT\_FF_i = WENG_i$		X	N/A	N/A
1.3.5.2.1	WT aligned with FF	**Alignment between FF and WT units** (UA)	UA = "aligned"		X	N/A	N/A
1.3.5.3	WT supply is sufficient to fill FF	**Quantitiy of water each WT_k has** (binary; full vs empty; k = 1 .. 2)	WT_k = "full" for all WTs		X	X_{WT}	X_{WT}

Annex B Goal templates

Assigned Operator	HUMAN				WORLD
1	INPUT	CENTRAL PROCESSING	OUTPUT		
Goal:	Required Knowledge states	Perceptual/ Cognitive processes	Ending conditions	Ending effects	Influenced Variable(s) (External)
1 Area is safe	**Declarative (training):** **Units' capabilities:** speed of movement, visual field (FF/WT/RT); time to extingusih fire (FF); water supply needed to sustain fire-fighting (WT) **Operators' duties and assignments** **Fire-fighting strategies**	**Visual** -centrall; **Cognitive** -automotized; -spatial pattern recognition; -reasoning	Time = Allocated Time (end of simulation)	Nfires = 0 (Al fires are extinguished);	EV1: --- number of fires
	Situational (real-time info requirements): Wind: direction and speed; Forests: type, size, and location; Houses: locations, density, type of forests adjacent; Other objects: source of water; Postions of units				
	Initiating conditions	LIST OF IPME TASKS	Influenced Variable(s) (Internal)		NOTES
	Time = 0;	* Area is safe	Overall status of fires in the area; State of fire-fighting and reconnaissance activities		

<table>
<tr><td>Assigned Operator</td><td colspan="4">HUMAN</td><td rowspan="2">WORLD</td></tr>
<tr><td>2</td><td>INPUT</td><td>CENTRAL PROCESSING</td><td colspan="2">OUTPUT</td></tr>
<tr><td>Goal:</td><td>Required Knowledge states</td><td>Perceptual/ Cognitive processes</td><td>Ending conditions</td><td>Ending effects</td><td>Influenced Variable(s) (External)</td></tr>
<tr><td>1.1 Area is searched</td><td><u>Declarative:</u>

Effective search strategies:
-tactics for mapping searched areas;
-optimal search paths when multiple units are involved;

RT units' capabilities:
-speed of movement, visual field, optimal search path</td><td rowspan="2">Visual
-central;

Cognitive
-automotized;
-spatial pattern recognition;
-reasoning</td><td rowspan="2">% Area searched = 100;
Time = Allocated Time</td><td rowspan="2"></td><td rowspan="2">EV1: ---
Percentage of area searched</td></tr>
<tr><td></td><td><u>Situational:</u>

Postions of units;
Allocation of units;
Mapping of searched areas</td></tr>
<tr><td></td><td>Initiating conditions</td><td>LIST OF IPME TASKS</td><td colspan="2">Influenced Variable(s) (Internal)</td><td>NOTES</td></tr>
<tr><td></td><td>% Area searched < 100;</td><td>SEARCH network:
* Area is searched</td><td colspan="2">Fire search status: what has been searched so far</td><td>Re-allocation of FF and WT units upon detecting a fire</td></tr>
</table>

<table>
<tr><td>Assigned Operator</td><td colspan="4">HUMAN</td><td rowspan="2">WORLD</td></tr>
<tr><td>1</td><td>INPUT</td><td>CENTRAL PROCESSING</td><td colspan="2">OUTPUT</td></tr>
<tr><td>Goal:</td><td>Required Knowledge states</td><td>Perceptual/ Cognitive processes</td><td>Ending conditions</td><td>Ending effects</td><td>Influenced Variable(s) (External)</td></tr>
<tr><td>1.1.1 Each unit is assigned to destination</td><td><u>Declarative:</u>

General guidelines for assigning units to fires based on units' capabilities:
-speed of movement;
-time to extinguish fire;
-water supply required to sustain fire-fighting (WT)</td><td rowspan="2">Visual
-central;

Cognitive
-spatial pattern recognition;
-reasoning

NON-IPME categories
-memory (Memorization)</td><td rowspan="2">D_{xy} set for all units;</td><td rowspan="2"></td><td rowspan="2">EV1: ---
$D_{x,y}$
(Assignments of each unit FF_j, WT_k, & RT_m to a destination)</td></tr>
<tr><td></td><td><u>Situational:</u>

Situation assesment:
-fire extent and shape of fire,
-location of houses relative to wind direction,
-location of forests relative to wind direction,
-number of units available,
-distance from fire(s) to nearest unit(s)

Information updates between O1 & O2: (Functional condition only)
-current locations of units,
-assigned locations</td></tr>
<tr><td></td><td>Initiating conditions</td><td>LIST OF IPME TASKS</td><td colspan="2">Influenced Variable(s) (Internal)</td><td>NOTES</td></tr>
<tr><td></td><td>D_{xy} is not set</td><td>* AssignTagToUnit;
* GetUnitCoordinate;
* AllocateUnit</td><td colspan="2">Status of units assignments</td><td>Once assignments are completed, operators concentrate on monitoring of fire-figting and recon info</td></tr>
</table>

Assigned Operator	HUMAN					WORLD
2	INPUT		CENTRAL PROCESSING	OUTPUT		
Goal:	**Required Knowledge states**		**Perceptual/ Cognitive processes**	**Ending conditions**	**Ending effects**	**Influenced Variable(s) (External)**
1.1.1.1 Areas with fast-burning forests are searched	**Declarative:** -Effective forest fire search strategy; -Tactics for mapping searched areas; -Search techniques when multiple units are involved **Situational:** **Fire-searching adopted to:** -wind direction, -size and type of forestation; -proximity of houses to forest, -number of units available, -location and extent of fire, -type of fire (house vs. forest) **Periodic information updates between operators (Functional condition only)**: searched cells, detected fires, active units		**Visual** -central; **Cognitive** -automotized; -spatial pattern recognition		X_{af}--; (counter for assigned units to the area)	EV1: --- Number of units searching for fire in area X_{af} (af = 1..nf; nf is a number of areas with forests)
	Initiating conditions	**Beginning effects**	**LIST OF IPME TASKS**	**Influenced Variable(s) (Internal)**		**NOTES**
	FBF_a < 1 for each a	Xaf++; (counter for assigned units to the area)	* Conduct forest search; * Manage resources	Status of forest-fire search		When fire detected: -search path will be revised; -units will be re-allocated

Assigned Operator	HUMAN				WORLD
2	INPUT	CENTRAL PROCESSING	OUTPUT		
Goal:	Required Knowledge states	Perceptual/ Cognitive processes	Ending conditions	Ending effects	Influenced Variable(s) (External)
1.1.1.2 Other objects are searched	**Declarative:** -Effective search strategy; -Tactics for mapping searched areas; -Search techniques when multiple units are involved	**Visual** -central; **Cognitive** -automotized; -spatial pattern recognition		TSU--;	EV1: --- TSU number of units searching for non-FBF fire
	Situational: **Fire-searching adopted to:** -wind direction, -size and type of forestation; -proximity of houses to forest, -number of units available, -location and extent of fire, -type of fire (house vs. forest) **Periodic information updates between operators (Functional condition only)**: searched cells, detected fires, active units				

	Initiating conditions	Beginning effects	LIST OF IPME TASKS	Influenced Variable(s) (Internal)	NOTES
	TSU < 1 (total N of searching units involved in non-FBF search	TSU++; (counter for assigned units for search)	* Conduct forest search; * Manage resources	Status of forest-fire search	When fire detected: -search path will be revised; -units will be re-allocated

Assigned Operator	HUMAN				WORLD
1	INPUT	CENTRAL PROCESSING	OUTPUT		
Goal:	**Required Knowledge states**	**Perceptual/ Cognitive processes**	**Ending conditions**	**Ending effects**	**Influenced Variable(s) (External)**
1.1.1.3 Units en route to assigned destination	**Declarative:** -Optimal starting points of fire-fighting **FF units' capabilities:** speed of movement, visual field **WT unit's capabilities:** speed of movement	**Visual** -central; **Cognitive** -automotized; -spatial pattern recognition **NON-IPME categories**		ENR_{jkm}--;	EV1: --- Number of units en route (ENR_{jkm}) (jkm = 1 to tu; tu is a total number of units j+k+m)
	Situational: -properties of houses (clustering, number); -fire extent and shape of fire; -wind direction; -adjacent forests; -type of forest; -location of units relative to fire location				
	Initiating conditions	**LIST OF IPME TASKS**	**Influenced Variable(s) (Internal)**		**NOTES**

Notes. The goal is get all units that have not yet arrived to move to their destinations.

<table>
<tr><th>Assigned Operator</th><th colspan="4">HUMAN</th><th rowspan="2">WORLD</th></tr>
<tr><th>1</th><th>INPUT</th><th>CENTRAL PROCESSING</th><th colspan="2">OUTPUT</th></tr>
<tr><th>Goal:</th><th>Required Knowledge states</th><th>Perceptual/ Cognitive processes</th><th>Ending conditions</th><th>Ending effects</th><th>Influenced Variable(s) (External)</th></tr>
<tr><td>1.2 Fires are prioritized</td><td><u>Declarative:</u>

General guidelines for piority setting that consider:
-important objects;
-type of forest;
-properties of houses (clustering, number)</td><td rowspan="2">Visual
-central;

Cognitive
-automotized;
-spatial pattern recognition;
-reasoning

NON-IPME categories
-memory (Memorization)</td><td rowspan="2">Fire with highest priority set (PF1 = x,y)</td><td rowspan="2">Initiate process of setting next highest priority fire</td><td rowspan="2">EV1: ---
Priority of fire (PF)</td></tr>
<tr><td></td><td><u>Situational:</u>

Situation assessment:
-fire extent and shape of fire,
-location of houses relative to wind direction,
-location of forests relative to wind direction,
-type of forest,
-location of units relative to fire location</td></tr>
<tr><td></td><td>Initiating conditions</td><td>LIST OF IPME TASKS</td><td colspan="2">Influenced Variable(s) (Internal)</td><td>NOTES</td></tr>
<tr><td></td><td>PF1 is not set</td><td>* Ranking in the same area;
* Ranking in different areas</td><td colspan="2"></td><td></td></tr>
</table>

Notes. The goal is to set a ranking of fires in terms of their characteristics (type of forest, extent, location, etc.). IPME tasks separation on same vs. different location is based on the situation where either one or more fires occur at the same time.

<table>
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<tr><td>2</td><td>INPUT</td><td>CENTRAL PROCESSING</td><td colspan="2">OUTPUT</td></tr>
<tr><td>Goal:</td><td>Required Knowledge states</td><td>Perceptual/ Cognitive processes</td><td>Ending conditions</td><td>Ending effects</td><td>Influenced Variable(s) (External)</td></tr>
<tr><td>1.2.1 Extent of fire is known</td><td>Declarative:

Effective fire-mapping techniques;
Dynamics of fire spread;
Co-ordiantion tactics for mapping fire when mulitple units involved</td><td rowspan="2">Visual
-centrall;

Cognitive
-automotized;
-spatial pattern recognition;
-reasoning

NON-IPME categories
-memory (Memorization)</td><td rowspan="2">$EP_{i,xy}$ set for all i</td><td rowspan="2">RT_m--;
(An RT unit becomes available)</td><td rowspan="2">EV1: ---
$EP_{i,xy\ br}$;
(Co-ordinates of border points outlying the extent of fire Fi;

i = 1..N, N number of fires;

xy a pair of co-ordinate outlying Fi;

br = 1..4, br is border; four br pairs of xy define the most West, North, East, & South co-ordintnes of each fire</td></tr>
<tr><td></td><td>Situational:

Fire-mapping adopted to:
-location of objects relative to wind direction,
-number of units available,
-type and size of fire

Periodic information updates between operators:
-fire extent and shape of fire,
-allocation of units,
-new assignemnts</td></tr>
<tr><td></td><td>Initiating conditions</td><td>LIST OF TASKS</td><td colspan="2">Influenced Variable(s) (Internal)</td><td>NOTES</td></tr>
<tr><td></td><td>$F_i \geq 1$ (at least one fire)</td><td>* Initiate fire mapping</td><td colspan="2">Status of fire-mapping activities</td><td></td></tr>
</table>

Assigned Operator	HUMAN				WORLD
1	INPUT	CENTRAL PROCESSING	OUTPUT		
Goal:	Required Knowledge states	Perceptual/ Cognitive processes	Ending conditions	Ending effects	Influenced Variable(s) (External)
1.2.2 Fires adjacent to downwind objects receive higher priority	**Declarative:** Effect of wind on fire spreading speed	**Visual** -central; **Cognitive** -automotized; -spatial pattern recognition; -reasoning **NON-IPME categories** -memory (Memorization)	Priority of fires according to wind direction: $PF_{di} < PF_{ui}$; PF_{di} down-wind object; PF_{ui} up-wind object	Initiate process of setting next highest priority object	EV1: --- Priority of fire (PF)
	Situational: **Situation assessment:** -wind direction and strength				
	Initiating conditions	LIST OF IPME TASKS	Influenced Variable(s) (Internal)		NOTES
	PF1 is not set	* Ranking in the same area; * Ranking in different areas			More than one item can receive same ranking; Some details how ranking done when both within- and between-areas fires are ranked

Assigned Operator	HUMAN				WORLD
1	INPUT	CENTRAL PROCESSING	OUTPUT		
Goal:	Required Knowledge states	Perceptual/ Cognitive processes	Ending conditions	Ending effects	Influenced Variable(s) (External)
1.2.3 Fast-burning forests receive higher priority	**Declarative:** Effect of types of forests on fire spreading speed	**Visual** -central; **Cognitive** -automotized; -spatial pattern recognition; -reasoning **NON-IPME categories** -memory (Memorization)	Priority of fires according to type of forest: $PF_{dfi} < PF_{sfi}$; PF_{ffi} fast-buring forest; PF_{sfi} slow-buring forest	Initiate process of setting next highest priority forest	EV1: --- Priority of fire (PF)
	Situational: **Situation assessment:** -type of forest at the fire; -extent of fire				
	Initiating conditions	LIST OF TASKS	Influenced Variable(s) (Internal)		NOTES
	PF1 is not set	* Ranking in the same area; * Ranking in different areas			More than one item can receive same ranking; Some details how ranking done when both within- and between-areas fires are ranked

Assigned Operator	HUMAN				WORLD
1	INPUT	CENTRAL PROCESSING	OUTPUT		
Goal:	Required Knowledge states	Perceptual/ Cognitive processes	Ending conditions	Ending effects	Influenced Variable(s) (External)
1.2.4 Larger fires receive higher priority	**Declarative:** Effect of fire size on fire spreading speed	**Visual** -central; **Cognitive** -automotized; -spatial pattern recognition; -reasoning **NON-IPME categories** -memory (Memorization)	Priority of fires according to their sizes: $PF_{fi} < PF_{fj}$; PF_{fi} fire with larger area; PF_{fj} fire with smaller area	Initiate process of setting next highest priority forest	EV1: --- Priority of fire (PF)
	Situational: **Situation assessment:** -extent of forest fire; -type of forest at the fire				
	Initiating conditions	LIST OF TASKS	Influenced Variable(s) (Internal)		NOTES
	PF1 is not set	* Ranking in different areas			More than one item can receive same ranking; Some details how ranking done when both within- and between-areas fires are ranked

<table>
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<tr><td>1</td><td>INPUT</td><td>CENTRAL PROCESSING</td><td colspan="2">OUTPUT</td></tr>
<tr><td>Goal:</td><td>Required Knowledge states</td><td>Perceptual/ Cognitive processes</td><td>Ending conditions</td><td>Ending effects</td><td>Influenced Variable(s) (External)</td></tr>
<tr><td>1.3 Fire is extinguished</td><td>Declarative:

-General strategies for fighting fires;
-Fire-fighting tactics when multiple units are involved;

FF units' capabilities:
speed of movement, visual field, fire-fighting speed, duration of fire-fighting on a single water refill

WT unit's capabilities:
speed of movement, water supply that each WT unit can provide without re-filling</td><td rowspan="2">Visual
-central;

Cognitive
-automotized;
-spatial pattern recognition;
-reasoning

NON-IPME categories</td><td rowspan="2">$S_i = 0$ for all i's</td><td rowspan="2">ENG_{hi}--;</td><td>EV1: ---
Number of burning fire cells (S_i) at fire F_i (i = 1..n; n is a number of fires)</td></tr>
<tr><td></td><td>Situational:

-properties of houses (clustering, number);
-fire extent and shape of fire;
-wind direction;
-adjacent forests;
-type of forest;
-location of units relative to fire location

Periodic information updates between operators:
active fires, active units, fire spread rate, water supply needed</td><td></td></tr>
<tr><td></td><td>Initiating conditions</td><td>LIST OF TASKS</td><td colspan="2">Influenced Variable(s) (Internal)</td><td>NOTES</td></tr>
<tr><td></td><td>$S_i \geq 1$ (at least one fire cell at fire F_i)</td><td>* Fire-fighting</td><td colspan="2">Status of fire-fighting</td><td></td></tr>
</table>

Assigned Operator	HUMAN				WORLD
1	INPUT	CENTRAL PROCESSIN	OUTPUT		
Goal:	**Required Knowledge states**	**Perceptual/ Cognitive processes**	**Ending conditions**	**Ending effects**	**Influenced Variable(s) (External)**
1.3.1 Number of FF units is sufficient to extinguish fire	**Declarative:** -General methods of estimating number of fire fighting units required (effect of type of forestation, shape of fires, etc.); **FF units' capabilities:** fire-fighting speed, duration of fire-fighting on a single water refill **WT unit's capabilities:** speed of movement, water supply that each WT unit can provide without re-filling	**Visual** -central; **Cognitive** -automotized; -spatial pattern recognition; -reasoning **NON-IPME categories:** -memory	**$ENG_{hi} \geq S_i / FFE_i$** -**Si** is a number of burning cells at fire Fi; -**FFEi** is a number of burning cells at fire Fi a single FF unit can extinguish; -**FFE_i / S_i** is number of units needed to extinguish the fire		Number of FF units fighting fire (ENG_{hi})
	Situational: -fire extent and shape of fire; -wind direction; -adjacent forests; -type of forest; -location of units relative to fire location **Periodic information updates between operators:** active fires, active units, fire spread rate				
	Initiating conditions	**LIST OF TASKS**	**Influenced Variable(s) (Internal)**		**NOTES**
	$ENG_{hi} < S_i / FFE_i$	* Initiate fire-fighting	Allocation status		

<table>
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<tr><td>1</td><td>INPUT</td><td>CENTRAL PROCESSING</td><td colspan="2">OUTPUT</td></tr>
<tr><td>Goal:</td><td>Required Knowledge states</td><td>Perceptual/ Cognitive processes</td><td>Ending conditions</td><td>Ending effects</td><td>Influenced Variable(s) (External)</td></tr>
<tr><td>1.3.1.1 Size of extinguishable fire is estimated</td><td><u>Declarative:</u>

FF units' capabilities:
fire-fighting speed, duration of fire-fighting on a single water refill

WT unit's capabilities:
speed of movement, water supply that each WT unit can provide without re-filling</td><td rowspan="2">Visual
-central;

Cognitive
-automotized;
-spatial pattern recognition;
-reasoning

NON-IPME categories:
-memory</td><td rowspan="2">FFE_i is set</td><td rowspan="2"></td><td>Number of burning cells at fire F_i a single FF unit can extinguish (FFE_i)</td></tr>
<tr><td></td><td><u>Situational:</u>

-shape of fire;
-wind direction;
-type of forest;
-location of units relative to fire location;

Periodic information updates between operators:
extent of fire, fire spread rate</td><td></td></tr>
<tr><td></td><td>Initiating conditions</td><td>LIST OF TASKS</td><td colspan="2">Influenced Variable(s) (Internal)</td><td>NOTES</td></tr>
<tr><td></td><td>FFE_i is not set</td><td>* Initiate fire-fighting</td><td colspan="2">Status of fire evaluation</td><td></td></tr>
</table>

<table>
<tr><th>Assigned Operator</th><th colspan="4">HUMAN</th><th rowspan="2">WORLD</th></tr>
<tr><td>1</td><td>INPUT</td><td>CENTRAL PROCESSING</td><td colspan="2">OUTPUT</td></tr>
<tr><td>Goal:</td><td>Required Knowledge states</td><td>Perceptual/ Cognitive processes</td><td>Ending conditions</td><td>Ending effects</td><td>Influenced Variable(s) (External)</td></tr>
<tr><td>1.3.2 FF on scene of fire area</td><td>Declarative:

-General strategies for fighting house fires;
-Optimal starting points of fire-fighting;
-Fire-fighting tactics when multiple units are involved;

FF units' capabilities:
speed of movement, visual field, fire-fighting speed, duration of fire-fighting on a single water refill

WT unit's capabilities:
speed of movement, water supply that each WT unit can provide without re-filling</td><td rowspan="2">Visual
-central;

Cognitive
-automotized;
-spatial pattern recognition

NON-IPME categories</td><td rowspan="2">$ENG_{hi} \geq 1$ for all hi's</td><td rowspan="2">ENG_{hi}++;</td><td rowspan="2">EV1: ---
Number of FF units on scene (ENG_{hi})
(hi = 1..h; h is number of fires)</td></tr>
<tr><td></td><td>Situational:

-properties of houses (clustering, number);
-fire extent and shape of fire;
-wind direction;
-adjacent forests;
-type of forest;
-location of units relative to fire location</td></tr>
<tr><td></td><td>Initiating conditions</td><td>LIST OF TASKS</td><td colspan="2">Influenced Variable(s) (Internal)</td><td>NOTES</td></tr>
<tr><td></td><td>ENG_{hi} = 0 for at least one fire</td><td>* Fire-fighting</td><td colspan="2"></td><td></td></tr>
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<tr><td>1.3.2.1 FF en route to fire area</td><td><u>Declarative:</u>

-Optimal starting points of fire-fighting

FF units' capabilities:
speed of movement, visual field

WT unit's capabilities:
speed of movement</td><td rowspan="2">Visual
-central;

Cognitive
-automotized;
-spatial pattern recognition

NON-IPME categories</td><td rowspan="2">$ENR_i \geq 1$ for all i's</td><td rowspan="2">ENR_i--;</td><td rowspan="2">EV1: ---
Number of FF units en route (ENR_i)
(i = 1..h; h is number of fires)</td></tr>
<tr><td></td><td><u>Situational:</u>

-properties of houses (clustering, number);
-fire extent and shape of fire;
-wind direction;
-adjacent forests;
-type of forest;
-location of units relative to fire location</td></tr>
<tr><td></td><td>Initiating conditions</td><td>LIST OF TASKS</td><td colspan="2">Influenced Variable(s) (Internal)</td><td>NOTES</td></tr>
<tr><td></td><td>ENR_i = 0 for at least one house fire</td><td>* Transportation to fire site</td><td colspan="2"></td><td></td></tr>
</table>

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<tr><td>1.3.3 FF water supply is efficient to fight fire</td><td><u>Declarative:</u>

FF unit's capabilities:
-water supply that FFunit has;
-amount of water needed to extinguish a single cell</td><td rowspan="2">Visual
-central;

Cognitive
-automotized;
-spatial pattern recognition;
-reasoning

NON-IPME categories</td><td rowspan="2">FF_k = "full" for all FF units</td><td rowspan="2"></td><td>Quantitiy of water each FF_k has (binary; full vs empty; k = 1 .. 4)</td></tr>
<tr><td></td><td><u>Situational:</u>

-shape of fire;
-wind direction;
-type of forest;
-location of units relative to fire location;
-location of WT units

Periodic information updates between operators:
extent of fire, fire spread rate, water level</td><td></td></tr>
<tr><td></td><td>Initiating conditions</td><td>LIST OF IPME TASKS</td><td colspan="2">Influenced Variable(s) (Internal)</td><td>NOTES</td></tr>
<tr><td></td><td>FF_k = "near empty" (less than amount of water to extinguish a single fire cell) for at least one FF unit</td><td>Water supply</td><td colspan="2"></td><td></td></tr>
</table>

Assigned Operator	HUMAN					WORLD
1	INPUT	CENTRAL PROCESSING	OUTPUT			
Goal:	Required Knowledge states	Perceptual/ Cognitive processes	Ending conditions	Ending effects	Influenced Variable(s) (External)
1.3.3.1 FF aligned with WT	<u>**Declarative:**</u> -Co-ordination when multiple units are involved; -Understanding re-fill rules **FF units' capabilities:** -Speed of movement, visual field	**Visual** -central; **Cognitive** -automotized; -spatial pattern recognition **NON-IPME categories**	UA == true;		EV: ---- Alignment between FF and WT units (UA)
	<u>**Situational:**</u> -location of WT units -establishing visual conatact				
	Initiating conditions	LIST OF IPME TASKS	Influenced Variable(s) (Internal)		NOTES

Assigned Operator	HUMAN				WORLD
1	INPUT	CENTRAL PROCESSING	OUTPUT		
Goal:	Required Knowledge states	Perceptual/ Cognitive processes	Ending conditions	Ending effects	Influenced Variable(s) (External)
1.3.4 Fire is closed-out	**Declarative:** -Tactics for closing-out unmanagable fire; -Fire-fighting tactics when multiple units are involved; **FF units' capabilities:** speed of movement, visual field, fire-fighting speed, duration of fire-fighting on a single water refill **WT unit's capabilities:** speed of movement, water supply that each WT unit can provide without re-filling	**Visual** -central; **Cognitive** -automotized; -spatial pattern recognition; -reasoning **NON-IPME categories**	$XB_i = 0$	ENG_{hi}--;	Number of burning cells without barrier (XB_i) for fire F_i
	Situational: -properties of houses (clustering, number); -fire spreading rate, extent and shape; -wind direction; -adjacent forests; -type of forest; -location of units relative to fire location **Periodic information updates between operators:** active fires, active units, fire spread rate, water supply needed				
	Initiating conditions	LIST OF IPME TASKS	Influenced Variable(s)		NOTES
	$F_i \geq 1$ (at least one fire); $XB_i > 0$; Fire F_i cannot be completely extinguished	* Fire-fighting	Status of fire-fighting		

Assigned Operator	HUMAN				WORLD
1	INPUT	CENTRAL PROCESSING	OUTPUT		
Goal:	Required Knowledge states	Perceptual/ Cognitive processes	Ending conditions	Ending effects	Influenced Variable(s) (External)
1.3.4.1 Fire contained	**Declarative:** -Tactics for containing unmanagable fire; -Fire-fighting tactics when multiple units are involved; **FF units' capabilities:** speed of movement, visual field, fire-fighting speed, duration of fire-fighting on a single water refill **WT unit's capabilities:** speed of movement, water supply that each WT unit can provide without re-filling	**Visual** -central; **Cognitive** -automotized; -spatial pattern recognition; -reasoning **NON-IPME categories**	S_i - $PS_i \leq 0$ for all i's -S_i is a number of buring cells currently at fire Fi; -PS_i is a a number of buring cells at the previous moment at fire Fi)		Fire acceleration rate (S_i-PS_i) at fire F_i
	Situational: -fire extent and shape of fire; -wind direction; -adjacent forests and type of forest; -location of units relative to fire location **Monitoring fire and periodic information updates between operators:** active fires, active units, fire spread rate, water supply needed				
	Initiating conditions	LIST OF IPME TASKS	Influenced Variable(s) (Internal)		NOTES
	S_i - PS_i > 0 for all i's	* Fire-fighting	Status of fire-fighting		Unstable situation; with time fire will either be extigiushed/burned-out, or it can spread out of control

Assigned Operator	HUMAN				WORLD
1	INPUT	CENTRAL PROCESSING	OUTPUT		
Goal:	**Required Knowledge states**	**Perceptual/ Cognitive processes**	**Ending conditions**	**Ending effects**	**Influenced Variable(s) (External)**
1.3.4.1 Fire contained	**Declarative:** -Tactics for containing unmanagable fire; -Fire-fighting tactics when multiple units are involved; **FF units' capabilities:** speed of movement, visual field, fire-fighting speed, duration of fire-fighting on a single water refill **WT unit's capabilities:** speed of movement, water supply that each WT unit can provide without re-filling	**Visual** -central; **Cognitive** -automotized; -spatial pattern recognition; -reasoning **NON-IPME categories**	S_i - $PS_i \le 0$ for all i's -S_i is a number of buring cells currently at fire Fi; -PS_i is a a number of buring cells at the previous moment at fire Fi)		Fire acceleration rate (S_i-PS_i) at fire F_i
	Situational: -fire extent and shape of fire; -wind direction; -adjacent forests and type of forest; -location of units relative to fire location **Monitoring fire and periodic information updates between operators:** active fires, active units, fire spread rate, water supply needed				
	Initiating conditions	**LIST OF IPME TASKS**	**Influenced Variable(s) (Internal)**		**NOTES**
	S_i - PS_i > 0 for all i's	* Fire-fighting	Status of fire-fighting		Unstable situation; with time fire will either be extigiushed/burned-out, or it can spread out of control

<table>
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<tr><td>Goal:</td><td>Required Knowledge states</td><td>Perceptual/ Cognitive processes</td><td>Ending conditions</td><td>Ending effects</td><td>Influenced Variable(s) (External)</td></tr>
<tr><td>1.3.4.1.1 Number of FF units is sufficient to contain fire</td><td><u>Declarative:</u>

-General methods of estimating number of fire fighting units required (effect of type of forestation, shape of fires, etc.);

FF units' capabilities:
fire-fighting speed, duration of fire-fighting on a single water refill

WT unit's capabilities:
speed of movement, water supply that each WT unit can provide without re-filling</td><td rowspan="2">Visual
-central;

Cognitive
-automotized;
-spatial pattern recognition;
-reasoning

NON-IPME categories</td><td rowspan="2">ENG_{hi} = S_i / FFE_i

-Si is a number of burning cells at fire Fi;

-FFEi is a number of burning cells at fire Fi a single FF unit can extinguish;

-FFE_i / S_i is number of units needed to extinguish the fire</td><td rowspan="2"></td><td>Number of FF units fighting fire (ENG_{hi})</td></tr>
<tr><td></td><td><u>Situational:</u>

-fire extent and shape of fire;
-wind direction;
-adjacent forests;
-type of forest;
-location of units relative to fire location

Periodic information updates between operators:
active fires, active units, fire spread rate</td><td></td></tr>
<tr><td></td><td>Initiating conditions</td><td>LIST OF IPME TASKS</td><td colspan="2">Influenced Variable(s) (Internal)</td><td>NOTES</td></tr>
<tr><td></td><td>$ENG_{hi} < S_i / FFE_i$</td><td>* Initiate fire-fighting</td><td colspan="2"></td><td>Unstable state</td></tr>
</table>

Assigned Operator	HUMAN				WORLD
1	INPUT	CENTRAL PROCESSING	OUTPUT		
Goal:	**Required Knowledge states**	**Perceptual/ Cognitive processes**	**Ending conditions**	**Ending effects**	**Influenced Variable(s) (External)**
1.3.4.1.1.1 Size of managable fire is estimated	**Declarative:** **FF units' capabilities:** fire-fighting speed, duration of fire-fighting on a single water refill **WT unit's capabilities:** speed of movement, water supply that each WT unit can provide without re-filling **Situational:** -shape of fire; -wind direction; -type of forest; -location of units relative to fire location; **Periodic information updates between operators:** extent of fire, fire spread rate	**Visual** -central; **Cognitive** -automotized; -spatial pattern recognition; -reasoning **NON-IPME categories:** -memory	FFC_i is set		Number of burning cells at fire F_i a single FF unit can contain (FFC_i)
	Initiating conditions	**LIST OF IPME TASKS**	**Influenced Variable(s) (Internal)**		**NOTES**
	FFC_i is **not** set	* Initiate fire-fighting	Status of fire evaluation		

Assigned Operator	HUMAN					WORLD
2	INPUT	CENTRAL PROCESSING	OUTPUT			
Goal:	**Required Knowledge states**	**Perceptual/ Cognitive processes**	**Ending conditions**	**Ending effects**		**Influenced Variable(s) (External)**
1.3.5 Water supply is available to fight each fire	**Declarative:** **WT unit's capabilities:** speed of movement, water supply that each WT unit can provide without re-filling	**Visual** -central; **Cognitive** -automotized; -spatial pattern recognition; -reasoning **NON-IPME categories**	$WT_i \geq 1$ for all fires			Number of WT units assigned to each fire (WT_i)
	Situational: -shape of fire; -wind direction; -type of forest; -location of units relative to fire location; -location of water sources **Periodic information updates between operators:** extent of fire, fire spread rate					
	Initiating conditions	**LIST OF IPME TASKS**	**Influenced Variable(s) (Internal)**			**NOTES**
	$WT_i = 0$ for at least one fire	Water supply				

<table>
<tr><th>Assigned Operator
2</th><th colspan="5">HUMAN</th><th rowspan="2">WORLD</th></tr>
<tr><th></th><th>INPUT</th><th>CENTRAL PROCESSING</th><th colspan="2">OUTPUT</th></tr>
<tr><th>Goal:</th><th>Required Knowledge states</th><th>Perceptual/ Cognitive processes</th><th>Ending conditions</th><th>Ending effects</th><th>Influenced Variable(s) (External)</th></tr>
<tr><td>1.3.5.1 WT on scene of fire area</td><td><u>Declarative:</u>

-General strategies for efficient water supply;
-Optimal placement of WT units in relation to FF units, fire properties, and water sources;
-Co-ordination when multiple units are involved;

WT units' capabilities:
-Speed of movement, visual field, water-refill speed, duration of fire-fighting on a single water refill</td><td rowspan="2">Visual
-central;

Cognitive
-automotized;
-spatial pattern recognition

NON-IPME categories</td><td rowspan="2">$WT_i \geq 1$ for at least one WT unit</td><td rowspan="2">WT_i++;</td><td rowspan="2">EV1: ---
Number of WT units on scene (WT_i)
(hi = 1..h; h is number of fires)</td></tr>
<tr><td></td><td><u>Situational:</u>

-fire extent and shape of fire;
-wind direction;
-adjacent forests;
-type of forest;
-location of units relative to fire location</td></tr>
<tr><td></td><td>Initiating conditions</td><td>LIST OF IPME TASKS</td><td colspan="2">Influenced Variable(s) (Internal)</td><td>NOTES</td></tr>
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Assigned Operator	HUMAN				WORLD
2	INPUT	CENTRAL PROCESSING	OUTPUT		
Goal:	**Required Knowledge states**	Perceptual/ Cognitive processes	**Ending conditions**	**Ending effects**	**Influenced Variable(s) (External)**
1.3.5.1 WT en route to fire area	**Declarative:** **WT unit's capabilities:** speed of movement	**Visual** -central; **Cognitive** -automotized; -spatial pattern recognition **NON-IPME categories**	$WENR_i \geq 1$ for all hi's	$WENR_i$--;	EV1: --- Number of WT units en route ($WENR_i$) (i = 1..h; h is number of fires)
	Situational: -fire extent and shape of fire; -wind direction; -location of units relative to fire location				
	Initiating conditions	**LIST OF IPME TASKS**	**Influenced Variable(s) (Internal)**		**NOTES**
	$WENR_i = 0$ for at least one house fire	* Transportation to fire site			

Assigned Operator	HUMAN				WORLD
2	INPUT	CENTRAL PROCESSING	OUTPUT		
Goal:	**Required Knowledge states**	**Perceptual/ Cognitive processes**	**Ending conditions**	**Ending effects**	**Influenced Variable(s) (External)**
1.3.5.2 WT established visual contact with FF	**Declarative:** -Knowledge related to visual field properties; -Co-ordination when multiple units are involved; **WT units' capabilities:** -Speed of movement, visual field	**Visual** -central; **Cognitive** -automotized; -spatial pattern recognition **NON-IPME categories**	VCWT/FF == true;		EV: ---- Visual contact between WT and FF units ($VC_{WT/FF}$)
	Situational: -location of units relative to fire location -confirming FF unit location				
	Initiating conditions	**LIST OF IPME TASKS**	**Influenced Variable(s) (Internal)**		**NOTES**

Assigned Operator	HUMAN				WORLD
2	INPUT	CENTRAL PROCESSING	OUTPUT		
Goal:	Required Knowledge states	Perceptual/ Cognitive processes	Ending conditions	Ending effects	Influenced Variable(s) (External)
1.3.5.2.1 WT aligned with FF	<u>**Declarative:**</u> -Co-ordination when multiple units are involved; -Understanding re-fill rules **WT units' capabilities:** -Speed of movement, visual field	**Visual** -central; **Cognitive** -automotized; -spatial pattern recognition **NON-IPME categories**	UA == true;		EV: ---- Alignment between WT and FF units (UA)
	<u>**Situational:**</u> -location of FF units -establishing visual conatact				
	Initiating conditions	LIST OF IPME TASKS	Influenced Variable(s) (Internal)		NOTES

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<tr><td>1.3.5.3 Water supply is efficient to fill FF</td><td><u>Declarative:</u>

WT unit's capabilities:
speed of movement, water supply that each WT unit can provide without re-filling</td><td rowspan="2">Visual
-central;

Cognitive
-automotized;
-spatial pattern recognition;
-reasoning

NON-IPME categories</td><td rowspan="2">WT_k = "full" for all water units</td><td rowspan="2"></td><td>Quantitiy of water each WT_k has (binary; full vs empty; k = 1 .. 2)</td></tr>
<tr><td></td><td><u>Situational:</u>

-shape of fire;
-wind direction;
-type of forest;
-location of units relative to fire location;
-location of water sources

Periodic information updates between operators:
extent of fire, fire spread rate</td><td></td></tr>
<tr><td></td><td>Initiating conditions</td><td>LIST OF IPME TASKS</td><td colspan="2">Influenced Variable(s) (Internal)</td><td>NOTES</td></tr>
<tr><td></td><td>WT_k = "empty" for at least one WT unit</td><td>Water supply</td><td colspan="2"></td><td></td></tr>
</table>

List of symbols/abbreviations/acronyms/initialisms

CF	Canadian Forces
DDD	Dynamic Decision-Making
DND	Department of National Defence
DRDC	Defence Research & Development Canada
DRDKIM	Director Research and Development Knowledge and Information Management
FF	Fire Fighting unit
HGA	Hierarchical Goal Analysis HGA
IPME	Integrated Performance Modelling Environment
MEA	Means Ends Analysis
PCT	Perceptual Control Theory PCT
R&D	Research & Development
RT	Reconnaissance unit
WT	Water Tank unit

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